Spatial distributions of plasma parameters in conventional magnetron discharges in presence of nanoparticles

Alebia Chami, Cécile Arnas

► To cite this version:

Alebia Chami, Cécile Arnas. Spatial distributions of plasma parameters in conventional magnetron discharges in presence of nanoparticles. Journal of Plasma Physics, 2020. hal-02954792

HAL Id: hal-02954792

<https://hal.science/hal-02954792>

Submitted on 1 Oct 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 Spatial distributions of plasma parameters in 2 conventional magnetron discharges in presence 3 of nanoparticles

4 A. Chami¹ and C. Arnas^{1,†}

5 ¹ Aix-Marseille université, CNRS, PIIM, 13397 Marseille, France

6 (Received 26 May 2020; revised 31 July 2020; accepted 31 July 2020)

7 Two-dimensional spatial measurements of magnetic field and plasma parameters have
8 been performed in conventional magnetron DC discharges during the formation of
9 metallic nanoparticles. Correlations between the electron density and temperature
10 distributions, and the magnetic field geometry and strength have been established. A sharp
11 increase of the plasma potential is found on the edge of the last magnetic arch followed
12 by a decrease towards the anode plate and edges. It is shown that the spatial variation of
13 the plasma potential is at the origin of a potential well that can trap negatively charged
14 nanoparticles.

15 Key words: electric discharges, dusty plasmas, plasma diagnostics

† Email address for correspondence: cecile.arnas@univ-amu.fr

16 1. Introduction

17 Many studies have explored the mechanisms of nanoparticle (NP) formation in
18 low-temperature plasmas for various applications extending from electronics (Grieve,
19 Mulvaney & Grieser 2000), optics (Kelly et al. 2003), magnetism (Wei et al. 2009)
20 and catalysis (Cuenya 2010) to biology or medicine since nanoscale materials present
21 enhanced properties compared to those of bulk materials (Chauduri & Paria 2012). Various
22 ionization sources can be used in this domain such as radio-frequency discharges (Couedel
23 et al. 2010), microwave electron cyclotron resonance discharges (Ouaras et al. 2015; Rojo
24 et al. 2019) and DC discharges (Kishor Kumar, Couedel & Arnas 2014; Michau, Hassouni
25 & Arnas 2017) as well as magnetron sputtering discharges in a gas-aggregation system
26 (MS-GAS) (Kashtanov, Sirnov & Hippler 2007; Hartmann et al. 2012; Caillard et al. 2015)
27 and conventional magnetron discharges that we use for basic studies on NP formation
28 (Arnas et al. 2019). For a given plasma source, NP formation depends strongly on the
29 discharge conditions (geometry, magnetic field configuration if any, discharge current
30 and voltage, gas pressure and temperature). These conditions also determine the plasma
31 parameters at the origin of the charging, heating and transport of the NPs in the plasma
32 as well as their internal features such as morphology, size and crystallinity from which
33 potential applications can be considered. Plasma parameter measurements are therefore of
34 prime interest.

35 Few measurements have been reported on plasma parameters for the conditions of
36 magnetron discharges operating at rather high pressure for NP production. Langmuir
37 probes (LPs) were used in some cases in MS-GAS in a single position under the
38 racetrack (Koten et al. 2016), and recently in radial and axial directions of MS-GAS, when
39 the cathode is in a partially oxidized state (Kousal et al. 2017). Conversely, numerous
40 measurements and modelling were performed to describe magnetron discharges operating
41 at low pressure (< 0.05 mbar) (Field, Dew & Burrell 2002) in order to improve deposition
42 rates and specific coating qualities (Depla & Leroy 2012). For instance, a complete
43 study of the spatial variations of plasma potential was conducted to find the electron
44 $E \times B$ drift velocities near the cathode and in the plasma volume (Bradley, Thompson
45 & Aranda Gonzalvo 2001). A complete three-dimensional map of the plasma parameters

46 was established pointing out the racetrack region where the most intense ion bombardment
47 takes place (Palmero et al. 2004).

48 In this article, we present measurements in two spatial dimensions of the magnetic field
49 and plasma parameters of conventional DC magnetron discharges during the formation
50 of NPs. The latter are synthesized from the sputtering of the cathode in tungsten at an
51 argon pressure of 0.3 mbar. Measurements of the magnetic field were carried out with a
52 Hall probe without plasma and a LP was used to find the plasma parameters. Correlations
53 between the magnetic field strength and lines, and the spatial variations of the electron
54 density and temperature have been established. A sharp increase of the plasma potential
55 was found around the last magnetic arch allowing the deduction of the potential energy of
56 a negatively charged NP. A potential well was found and its role is discussed.

57 2. Experimental set-up and diagnostic procedures

58 The experimental set-up was already presented (Arnas et al. 2019) and is schematized
59 in figure 1. Experiments are conducted in a stainless steel cylinder of 40 cm in length
60 and 30 cm in diameter. The ionization source is an unbalanced planar magnetron system
61 (mcse-ROBEKO). The cathode is a tungsten disc (99.95 % purity) of 7.6 cm in diameter
62 and 0.3 cm in width. A grounded guard ring of 2 cm in width and 1 cm in height (~7.4 cm
63 inner diameter) is set under the cathode at a distance of ~0.2 cm. A grounded stainless
64 steel disc of 15 cm in diameter (anode plate) is placed parallel to the cathode at 10 cm. Two
65 half-glass cylinders, 12 cm in diameter and 10 cm long, are placed around this magnetron
66 system. In order to insert a LP in the plasma, the half-glass cylinders are separated by two
67 diametrically opposed gaps of ~1.5 cm.

68 Discharges are produced in argon at 0.3 mbar and 5 sccm (standard cubic centimetres
69 per minute) flow rate. The discharge current is maintained constant at 0.3 A using a
70 DC current-regulated power supply (Glassman HV, 1 A–1 kV) and the discharge voltage
71 self-adjusts to approximately –200 V. The formation of NPs and then their sampling are
72 carried out on stainless steel polished substrates, which are pushed one after the other
73 under a hole drilled in the centre of the anode disc. The description of their formation in
74 such discharge conditions and geometry as well as their structural properties were already
75 reported in (Arnas et al 2019) and will not be discussed in this article.

76 A Hall probe was used to measure the magnitude of the magnetic field when the
77 discharge was not operational. For this, a small gallium arsenide semiconductor plate
78 of 0.1 cm × 0.1 cm embedded in a thin long resin stripe linked to a gaussmeter

FIGURE 1. Experimental set-up. The lower-right part represents the top view of the two half-glass cylinders. They are slightly opened to allow introduction of a LP. This set-up is inside a stainless steel cylinder

79 (GM08-HIRST) was used. This sensor was displaced radially every 0.2 cm from $r = -5$
80 to $r = 5$ cm, 0 cm being the centre of the cathode. These measurements were repeated
81 vertically every 0.5 cm from 0.4 cm of the copper baking plate where the cathode plate is
82 fixed to the anode plate. Measurements were taken directly with the calibrated gaussmeter.
83 A homemade cylindrical LP consisting of a tungsten wire 0.0125 cm in diameter and
84 ~ 1 cm in length was used to measure the plasma parameters. The probe axis was displaced
85 radially, every centimetre from $r = -2$ to $r = 6$ cm (position of the glass tubes). The
86 same radial measurements were made by moving the probe vertically every centimetre
87 from $z = 2$ to $z = 9$ cm (or 1 cm above the anode plate). To avoid the LP contamination,
88 the plasma duration was limited to the time necessary for probe cleaning by electron
89 bombardment (several seconds, several times), and then to the time necessary to acquire
90 three LP characteristics in ~ 15 s. Several series of characteristics were obtained for a
91 given z and the LP was changed in every z position. A commercial driver (Princeton
92 Instruments) was used for LP cleaning and current-bias (I-V) acquisition every δV
93 ~ 200 mV. The I-V data were then collected with a 12-bit A/D convertor (National
94 Instruments). Homemade programs using the software Matlab allowed establishing the
95 spatial magnetic field strength and lines as well as the plasma parameters.

96 3. Spatial distribution of the magnetic field

97 Construction of the magnetic field lines and values (B in gauss) in colour are shown in
98 figure 2(a). The cathode is represented in black at $z = 0 - 0.3$ cm as well as the guard ring
99 under each cathode side. The magnetron is unbalanced: magnetic field arches are present
100 over a distance of $z \sim 3.8$ cm and a part of the magnetic field lines in the cathode centre
101 and peripheries is directed towards the anode plate. Red lines give some contour plots of
102 the magnetic field strength. Figure 2(b) shows the decrease of the magnetic field from the
103 cathode, axially (for $r = 0$ cm) as well as under the position of the so-called ‘racetrack’
104 ($r = 2$ cm) where the sputtering is maximum (under the magnetic field lines parallel to
105 the cathode) and under the edge of the cathode ($r = 4$ cm). At the cathode surface centre,
106 $B \sim 860$ G. The magnetic null point is at $z \sim 3.8$ cm. Its position in the colour map is in

FIGURE 2. (a) Magnetic field measurements from the cathode ($z = 0.3$ cm) to the grounded anode plate ($z = 10$ cm). Magnetic field line directions are represented by arrows; colours give the strength and some contour lines are in red. (b) Decrease of the magnetic field axially ($r = 0$ cm), under the racetrack ($r = 2$ cm) and under the cathode edge ($r = 3.8$ cm). Inset: magnified view from $z = 2$ cm where LP measurements were performed.

the centre of the closed contour lines. The magnified view in the inset of figure 2(b) also shows this position on the plasma axis. Moreover, the inset provides the detail of B from $z=2$ cm where LP measurements began to 10 cm. At $z=2$ cm, the maximum of B is ~ 130 G. For $z > 6$ cm, whatever the radial position, $B < 20$ G and at $z = 9 - 10$ cm, $B \sim 8$ G.

4. Spatial distribution of plasma parameters

Earlier studies have shown that the I–V characteristic of a cylindrical probe is not perturbed by magnetic fields if its axis is perpendicular to the magnetic field lines and if the probe radius r_p is small compared to the Larmor radius r_L of the charged particles. Hence, when $\beta = r_p/r_L \ll 1$, the magnetic field influence is neglected (Kolpakova, Kudrna & Tichy 2013). In our conditions, this condition was post-checked by an evaluation of $r_L \sim 400 \mu\text{m}$ at $z = 2$ cm in comparison with $r_p = 62.5 \mu\text{m}$ and confirmed for $z > 2$ cm, a region of a strong magnetic field decrease.

Assuming in a first approximation that only Ar atoms are ionized, the I–V characteristics of the LP have shown that the electron population is quasi-Maxwellian in the plasma plane, r – z . The plasma potential V_p was found from the first derivative or the inflexion point of the I–V curve after subtracting the saturation ion current of the total probe current. The electron density and temperature (n_e and T_e , respectively) were found classically: n_e from the expression of the electron saturation current of a cylindrical LP in V_p , and T_e by fitting the I–V characteristic curve by an exponential function from the probe floating potential to V_p .

Figures 3(a) and 3(b) show n_e and T_e variations, respectively, from $r = -2$ to $r = 6$ cm. Measurements from $r = -3$ to -6 cm are not reported. They were perturbed by shadowing effects of the insulating tube part of the LP which was translated horizontally from a single lateral window of the vacuum chamber. However, measurements from $r = 0$ to -2 cm show that the axial symmetry of the magnetron system is fulfilled. For greater clarity, measurement error bars are only shown for data obtained for $z = 9$ cm of figure 3(a) and for $z = 8$ cm of figure 3(b). In the latter case, the data symbol was reduced to show better the error bars.

Two regions are revealed in figure 3(a). In the region located before the null point, from $z = 2$ to ~ 4 cm, the maximum of n_e is inside the magnetic arches. Parameter n_e decreases towards the discharge axis and to lower values towards the half-glass cylinder position. The maximum at $z = 2$ cm is $\sim 1.5 \times 10^{17} \text{ m}^{-3}$. From the null point position to the anode plate, n_e is maximum on the discharge axis and decreases axially and radially.

FIGURE 3. (a) Electron density and (b) temperature measurements from $r = -2$ to 0 cm (axial position) and $r = 0$ to 6 cm (half-glass tube position), for various distances z to the cathode. Symmetric measurements with respect to the discharge axis were stopped at $r = -2$ cm because of LP shadowing effects.

Figure 3(b) shows the distributions of T_e . There is a minimum of T_e when n_e is maximum under the magnetic arches. A second minimum appears around $r \sim 4$ cm, the position of the guard ring of 1 cm in height (see figure 2 a). The maximum of $T_e \sim 1.8$ eV is reached at the plasma edge, in between the half-glass cylinders. Beyond the magnetic arches, T_e progressively decreases vertically as n_e does. The lower value, $T_e = 0.75$ eV, is obtained above the anode plate at $z = 9$ cm.

Figures 4(a)–4(c) provide, in the r - z plane, the variations in colour of n_e , T_e and V_p , respectively. The magnetic field lines are added in figure 4(a). They highlight the correlation existing between the position of the maximum plasma density and the position of the magnetic arches. They are not added in the colour map of T_e for more clarity, but it appears that in the arch regions, T_e has a minimum where the density is at maximum and then increases when the density decreases. The superimposition of magnetic field lines in figure 4(c) shows that V_p has negative values inside the magnetic arches, reaching -0.3 eV. A sharp increase is observed in the edge of the last magnetic arch. The largest positive values are under the guard ring and more generally in a central band, parallel to the cathode, from $z \sim 4$ to ~ 7 cm. This is also shown in figure 5(a) versus z from $r=0$ to 5 cm. This spatial distribution of V_p is at the origin of a potential well for NPs as presented in the next section.

FIGURE 4. Spatial distribution in colour in the (r, z) plane of (a) the electron density, (b) the electron temperature and (c) the plasma potential. Magnetic field lines are superimposed on the electron density and the plasma potential maps.

159 5. Equilibrium position of a nanoparticle

160 It has been shown (Arnas et al. 2019) that the mean size of NPs synthesized from
 161 tungsten sputtering in magnetron discharges similar to those described above is around
 162 20 nm after a 15 s discharge. The charging of an isolated dust particle is calculated
 163 classically using the orbital motion limited model where it is supposed that the ions and
 164 electrons have an orbital trajectory around the particle (Bernstein & Rabinowitz 1959).
 165 The equality between the electron and the ion flux at the NP surface provides the NP
 166 floating potential ϕ with respect to the plasma potential, from which one can deduce the
 167 NP negative charge. In the plasma volume, the expression of the ion flux is

$$168 \quad I_i(\phi) = \frac{S}{4} n_0 v_i \left(1 - \frac{2e\phi}{m_i v_i^2}\right), \quad (5.1)$$

169 where S is the NP surface, n_0 the plasma density and v_i the ion thermal velocity. The
 170 expression of the electron flux is

$$171 \quad I_e(\phi) = \frac{S}{4} n_0 v_e \exp\left(\frac{e\phi}{k_B T_e}\right), \quad (5.2)$$

172 where v_e is the electron thermal velocity. The negative charge is given by $Q_d = 4\pi\epsilon_0 r_d V_{\text{flot}}$,
 173 where r_d and V_{flot} are the NP radius and floating potential, respectively. Figure 5(b) shows
 174 the variations of Q_d in electron units versus z , for $r = 0$ to 5 cm. The maximum charge is
 175 reached in the cathode side for $z = 3$ to ~ 4 cm. Charge modulations are present along z
 176 but on average, the charge decreases from $z = 4$ to 9 cm.
 177 The potential energy of an isolated dust particle in every (r, z) position is due to the
 178 contributions of the electrostatic and gravitational forces:

$$179 \quad E_{\text{tot}} = Q_d V_p - m_d g(z_0 - z), \quad (5.3)$$

180 where m_d is the NP mass, g the gravity intensity and $z_0 = 10$ cm is the distance between
 181 the electrodes. The potential energy $m_d g(z_0 - z)$ is at least two orders of magnitude lower

FIGURE 5. Variations versus the distance z for $r = 0$ to 5 cm of (a) the plasma potential, (b) the charge in electron units of an isolated NP of 20 nm in size and (c) the potential energy of the NP deduced from the charge and the plasma potential distributions.

182 than $Q_d V_p$, everywhere. Figure 5(c) shows the variations of E_{tot} . A potential well is clearly
 183 evidenced at $z = 4$ cm for $r = 0$ to 2 cm, and likely to $r = 3$ cm. From $r = 4$ to 5 cm,
 184 E_{tot} presents modulations along z . The corresponding absolute values decrease on average
 185 from $z=2$ to $z=9$ cm.

186 6. Discussion

187 In the discharge axis and close to the cathode, the magnetic field has the largest values. It
 188 is directed perpendicularly to the cathode in contrast to the etch region where the magnetic
 189 field is parallel to the cathode. Hence, electrons move easily axially, being impeded from
 190 moving in a lateral direction. As a consequence, the plasma density is lower along the
 191 plasma axis and in all regions where the magnetic field lines are normal to the cathode.
 192 Moreover, when the magnetic field normal to the cathode drops, the electron gyro-radius
 193 increases and transport towards the lateral wall is also favoured, in particular from
 194 $z > 4$ cm. Meanwhile, electrons trapped in the high-field regions parallel to the cathode
 195 produce more ionization collisions.

196 Modelling at low pressure (Bogaerts, Kolev & Buyle 2008) has shown that for the
 197 discharge sustainment carried out by secondary electrons ejected from the cathode, the
 198 maximum ionization rate is located under the racetrack, in the sheath and also for a
 199 significant amount in the cathode pre-sheath. It was shown that the latter can have widths
 200 of several centimetres in magnetrons operating with strong magnetic field (Shidoji &
 201 Makabe 2003) and low pressure (Bradley et al. 2001; Shidoji & Makabe 2003). In our
 202 experimental conditions, the pre-sheath extends over ~ 2 cm from the cathode region
 203 where V_p is still negative. In the pre-sheath region to $z \sim 4$ cm, T_e and n_e are inversely
 204 proportional. This answers to a general trend in plasmas where in order to sustain the
 205 discharge, the electron temperature increases when the electron density decreases, in
 206 particular when there is diffusion towards the wall. From $z > 4$ cm towards the anode
 207 plate position, T_e and n_e decrease. Moreover, T_e decreases to values ≤ 1 eV indicating that
 208 electron ionization can no longer take place in this region.

209 The cooling of T_e in the presence of metallic atoms of lower ionization potential than the
 210 buffer gas has already been reported (Hopwood & Qian 1995; Sigurjonsson et al. 2009).
 211 The W ionization energy is 7.86 eV against 15.76 eV for Ar. We assume that W ionization
 212 is performed for $z < 2$ cm since no W^+ line has been observed for $z \geq 2$ cm in emission

spectra obtained in the visible range (not presented here), aiming in a direction parallel to the cathode. Therefore, the cooling of T_e when $z > 4$ cm is attributed to W excitation collisions with electrons. In particular for $z > 4$ cm, the plasma light emission decreases strongly. Only W atomic lines were found in this region (no Ar lines) and the plasma emission was almost non-existent for $z > 6$ cm. At low operating pressure, some modelling results confirmed experimentally have shown that when the plasma potential becomes positive after the pre-sheath, it progressively increases or saturates in the bulk plasma (Rosnagel & Kaufman 1986; Kondo & Nambu 1999; Bradley et al. 2001). In MS-GAS used for the production of titanium NPs at a pressure similar to ours, LP measurements have evidenced a progressive increase of V_p in the direction perpendicular to the cathode (Kousal et al. 2017). In our conditions, a sharp increase of V_p on the edge of the last magnetic arch has been highlighted and maximum values were measured in a rather central band, parallel to the cathode. The potential energy that a negatively charged NP can have in such a plasma potential distribution shows the presence of a potential well. NPs could have a stable position in this region.

7. Conclusion

Two-dimensional spatial distributions of plasma parameters were established in unbalanced magnetron discharges using a LP. The cathode material was tungsten and argon was used at a pressure of 0.3 mbar in order to produce NPs from cathode sputtering. The magnetic field lines and strength were also established without plasma, using a Hall probe. Despite the presence of NPs of ~ 20 nm in size on average, correlations were established between the magnetic field geometry and strength, and the spatial distributions of the electron density and temperature. These correlations are quite similar to those established in magnetron discharges operating at low pressure for material deposition processes. Differences were found in the plasma potential variations from the cathode pre-sheath region where the potential is negative towards the anode plate region. In particular, a sharp potential increase was evidenced on the edge of the last magnetic arch and the maximum values were found in a layer parallel to the electrodes. This particular distribution is at the origin of a NP potential well which was evidenced from the potential energy that an isolated NP of negative charge can reach. Subsequent experiments will be dedicated to investigating whether NPs can have a stable position in this region using the laser extinction method and also whether they could grow there by W deposition.

Acknowledgements

This work has been carried out within the framework of the French Federation for Magnetic Fusion Studies (FR-FCM) and the Eurofusion consortium, and has received funding from the Euratom research and training programme 2014–2018 and 2019–2020 under grant agreement no. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Editor Edward Thomas thanks the referees for their advice in evaluating this article.

Declaration of interests

The authors report no conflict of interest.

REFERENCES

- ARNAS, C., CHAMI, A., COUEDEL, L., ACSENTE, T., CABIE, M. & NEISIUS, T. 2019 Thermal balance of tungsten monocrystalline nanoparticles in high pressure magnetron discharges. *Phys. Plasmas* 26, 053706.
- BERNSTEIN, I. B. & RABINOWITZ, I. N. 1959 Theory of electrostatic probes in low-density plasma. *Phys. Fluids* 2, 112–121.
- BOGAERTS, A., KOLEV, I. & BUYLE, G. 2008 Modeling of the magnetron discharge. In *Reactive Sputter Deposition* (ed. D. Depla & S. Mahieu). Springer Series in Material Science, vol. 109, pp. 61–130.
- BRADLEY, J. W., THOMPSON, S. & ARANDA GONZALVO, Y. 2001 Measurements of the plasma potential in a magnetron discharge and the prediction of the electron drift speeds. *Plasma Sources Sci. Technol.* 10, 490–501.

CAILLARD, A., CUYNET, S., LECAS, T., ANDREAZZA, P., MIKIKIAN, M., THOMANN, A.-L. & BRAULT, P. 2015 PdPt catalyst synthesized using a gas aggregation source and magnetron sputtering for fuel cell electrodes. *J. Phys. D: Appl. Phys.* 48, 475302.

CHAUDURI, R. G. & PARIA, S. 2012 Core/shell nanoparticles: classes, properties, synthesis mechanisms, characterization, and applications. *Chem. Rev.* 112, 2373–2433.

COUEDEL, L., MIKIKIAN, M., SAMARIAN, A. A. & BOUFENDI, L. 2010 Self-excited void instability during dust particle growth in a dusty plasma. *Phys. Plasmas* 17, 083705.

CUENYA, R. C. 2010 Synthesis and catalytic properties of metal nanoparticles: size, shape, support, composition, and oxidation state effects. *Thin Solid Films* 518, 3127–3150.

DEPLA, D. & LEROY, W. P. 2012 Magnetron sputter deposition as visualized by Monte Carlo modeling. *Thin Solid Films* 520, 6337–6354.

FIELD, D. J., DEW, S. K. & BURRELL, R. E. 2002 Spatial survey of a magnetron plasma sputtering system using a Langmuir probe. *J. Vac. Sci. Technol. A* 20, 2032–2041.

GRIEVE, K., MULVANEY, P. & GRIESER, F. 2000 Synthesis and electronic properties of semiconductor nanoparticles/quantum dots. *Curr. Opin. Colloid Interface Sci.* 5, 168–172.

HARTMANN, H., POPOK, V. N., BARKE, I., VON OEYNHAUSEN, V. & MEIWES-BROER, K.-H. 2012 Design and capabilities of an experimental setup based on magnetron sputtering for formation and deposition of size-selected metal clusters on ultra-clean surfaces. *Rev. Sci. Instrum.* 83, 073304.

HOPWOOD, J. & QIAN, F. 1995 Mechanisms for highly ionized magnetron sputtering. *J. Appl. Phys.* 78, 758–765.

KASHTANOV, P. V., SIRNOV, B. M. & HIPPLER, R. 2007 Magnetron plasma and nanotechnology. *Phys.-Uspekhi* 50, 455–488.

KELLY, K. L., CORONADO, E., ZAHO, L. L. & SCHATZ, G. C. 2003 The optical properties of metal nanoparticles: the influence of size, shape, and dielectric environment. *J. Phys. Chem. B* 107, 668–677.

KISHOR KUMAR, K., COUEDEL, L. & ARNAS, C. 2014 Nanoparticles in direct current discharges: growth and electrostatic coupling. *J. Plasma Phys.* 80, 849–853.

KOLPAKOVA, A., KUDRNA, P. & TICHY, M. 2013 Langmuir probe diagnostics of DC cylindrical magnetron. In WDS' 13 Proceedings of Contributed Papers, Part II, pp. 127–133.

KONDO, S. & NAMBU, K. 1999 A self-consistent numerical analysis of a planar DC magnetron discharge by particle -in-cell/Monte Carlo method. *J. Phys. D: Appl. Phys.* 32, 1142–1152.

KOTEN, M. A., VOELLER, S. A., PATTERSON, M. M. & SHIELD, J. E. 2016 In situ measurements of plasma properties during gas-condensation of Cu nanoparticles. *J. Appl. Phys.* 119, 114306. KOUSAL, J., KOLPAKOVA, A., SHELEMIN, A., KUDRNA, P., TICHY, M., KYLIAN, O., HANUS, J.,

CHOUKOUROV, A. & BIEDERMAN, H. 2017 Monitoring of conditions inside gas aggregation cluster source during production of Ti/TiO_x nanoparticles. *Plasma Sources Sci. Technol.* 26, 1005003.

MICHAU, A., HASSOUNI, K. & ARNAS, C. 2017 Aerosol dynamics in a sputtering discharge. *J. Appl. Phys.* 121, 163301.

OUARAS, K., HASSOUNI, K., COLINA DELACQUA, L., LOMBARDI, G., VREL, D. & BONIN, X. 2015 Tungsten dust nanoparticles generation from blistering bursts under hydrogen environment in microwave ECR discharge. *J. Nucl. Mater.* 466, 65–68.

PALMERO, A., VAN HATTUM, E. D., ARNOLDBIK, W. M., VREDENBERG, A. M. & HABRAKEN, P. M. 2004 Characterization of the plasma in radio-frequency magnetron sputtering system. *J. Appl. Phys.* 95, 7611.

ROJO, M., GLAD, X., MARGOT, J., DAP, S. & CLERGERAUX, R. 2019 Charging and heating processes of dust particles in an electron cyclotron resonance plasma. *Plasma Sources Sci. Technol.* 28, 085004. ROSSNAGEL, S. M. & KAUFMAN, H. R. 1986 Langmuir probe characterization of magnetron operation. *J. Vac. Sci. Technol. A* 4, 1822–1825.

SIGURJONSSON, P., LARSSON, P., LUNDIN, D., HELMERSSON, U. & GUDMUNDSSON, J. T. 2009 Langmuir probe study of the plasma parameters in the HiPIMS discharge. In 52nd Annual Technical Conference Proceedings, Santa Clara, CA, ISSN 0737-5921.

WEI, X., SKOMSKI, R., BALAMURUGAN, B., SUN, Z. G., DUCHARMA, S. & SELLMYR, D. J. 2009 Magnetism of TiO and TiO₂ nanoclusters. *J. Appl. Phys.* 105, 07C517.